A Conservative DESI DR1 Radial-Velocity Variability Search for Unseen Companions

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Abstract

We present a conservative, reproducible search for statistically significant radial-velocity (RV) variability in public DESI Data Release 1 (DR1) Milky Way Survey (MWS) data. Using per-epoch RV measurements, we identify stars whose RV variability exceeds measurement noise and remains robust under leave-one-out tests. To filter for potential non-interacting compact companions (white dwarfs, neutron stars, black holes) rather than ordinary luminous binaries, we implement a "Negative Space" multi-messenger validation pipeline based on Gaia DR3 astrometry, WISE infrared photometry, TESS time-domain photometry, GALEX ultraviolet imaging, Legacy Survey (DECaLS) deep imaging, and external spectroscopy from LAMOST.

From an initial DESI RV-variable sample we identify a small set of systems with large RV excursions and astrometric evidence for non-single-star behavior. We highlight one object, **Gaia DR3 3802130935635096832**, as a high-priority unseen-companion *candidate*. This source shows large RV variations (ΔRV ≈ 146 km s^{-1} over 39 days in DESI), a multi-year LAMOST RV consistent with orbital motion, and elevated Gaia astrometric noise (RUWE = 1.95). LAMOST spectroscopy classifies the visible star as an M0 dwarf, implying a primary mass $M_1 \approx 0.5\, M_\odot$. The system exhibits no significant infrared excess, no GALEX UV detection, and no strong TESS variability. Circular-orbit fits to the combined LAMOST+DESI RVs favour periods of order tens of days; one such solution at $P \approx 15.9$ days and $K \approx 104$ km s^{-1} implies a mass function $f(M) \approx 1.85\, M_\odot$ and a minimum companion mass $M_{2,\mathrm{min}} \approx 2.6\, M_\odot$ for $M_1 = 0.5\, M_\odot$. However, with only five RV epochs this period is not uniquely determined, and cool white dwarfs, neutron stars, and black holes remain viable companions. We describe the selection, validation, and limitations of the current data and outline the RV monitoring required to determine the orbital period and dynamical mass of the unseen companion.

1 Introduction

Non-interacting compact objects—white dwarfs, neutron stars, and black holes—are expected to be abundant in the Milky Way, yet are observationally elusive when they are not accreting or otherwise luminous. Radial-velocity (RV) monitoring offers a purely gravitational detection channel: an unseen companion can be inferred from the reflex motion of a visible star. Large spectroscopic surveys such as DESI provide multi-epoch RVs for millions of stars, but these data are not primarily designed for binary searches, and robust identification of unseen companions requires carefully controlled selection and validation.

DESI DR1 delivers per-epoch RV measurements for the Milky Way Survey (MWS). Here we leverage these data to perform a conservative RV-variability search for unseen companions, with an emphasis on reproducible selection criteria and multi-messenger checks that identify systems with "strong gravity but missing light". Our aim is not to claim a definitive new compact object based solely on DR1, but to (i) demonstrate that DESI DR1 per-epoch RVs enable a clean, survey-scale search for high-amplitude RV variability, and (ii) construct a small list of well-characterized unseen-companion *candidates* suitable for dedicated follow-up.

2 Data

2.1 DESI DR1 Milky Way Survey RVs

We use public DESI DR1 MWS per-epoch RV products from the `main-bright` and `main-dark` programs. For each RV epoch we extract:

- heliocentric radial velocity RV,
- RV uncertainty $\sigma_{\rm RV}$,
- observation time (Modified Julian Date, MJD),
- DESI target identifier,
- Gaia `SOURCE_ID` when available.

Gaia identifiers are used solely for cross-referencing and do not enter the RV selection.

2.2 External Data: Gaia, WISE, TESS, GALEX, Legacy Surveys, LAMOST

For RV-variable candidates we cross-match to:

- Gaia DR3 for astrometric parameters (parallax, RUWE, astrometric excess noise),
- 2MASS and WISE for near- and mid-infrared photometry,
- TESS Full Frame Images (FFIs) for time-domain optical photometry,
- GALEX for near-ultraviolet imaging,
- Legacy Survey (DECaLS) imaging for crowding and blending checks,
- LAMOST for independent spectra and RVs when available.

3 RV-Variability Selection

3.1 Per-Epoch Quality Cuts

We apply the following per-epoch quality cuts:

1. finite RV and $\sigma_{\rm RV}$,
2. $\sigma_{\rm RV} < 10\ {\rm km\,s^{-1}}$,
3. $|{\rm RV}| < 500\ {\rm km\,s^{-1}}$.

These cuts remove pathological RV fits while retaining the vast majority of valid measurements.

3.2 Variability Metrics

For each star with N RV epochs we define:

$$\Delta \mathrm{RV}_{\max} = \max(\mathrm{RV}) - \min(\mathrm{RV})\,, \tag{1}$$

and a noise-weighted significance metric:

$$S = \frac{\Delta \mathrm{RV}_{\max}}{\sqrt{\sum_{i=1}^{N} \sigma_{\mathrm{RV},i}^2}}\,. \tag{2}$$

Table 1: Symbol definitions for the RV variability metrics.

Symbol	Definition
$\Delta \mathrm{RV}_{\max}$	Maximum difference between any two measured RVs for a star ($\mathrm{km\,s^{-1}}$)
RV	Measured heliocentric radial velocity at a given epoch ($\mathrm{km\,s^{-1}}$)
S	Noise-weighted significance of RV variability (dimensionless)
N	Number of RV epochs for the star (dimensionless)
$\sigma_{\mathrm{RV},i}$	Uncertainty in the i^{th} RV measurement ($\mathrm{km\,s^{-1}}$)

3.3 Robustness Diagnostics

To guard against single-epoch artifacts we compute a leave-one-out minimum significance $S_{\mathrm{min,LOO}}$ by recomputing S after removing each epoch in turn and taking the minimum:

$$S_{\mathrm{min,LOO}} = \min_j \left[\frac{\Delta \mathrm{RV}_{\max}^{(j)}}{\sqrt{\sum_{i \neq j} \sigma_{\mathrm{RV},i}^2}} \right]\,, \tag{3}$$

where $\Delta \mathrm{RV}_{\max}^{(j)}$ denotes the maximum RV excursion computed with epoch j removed.

We then define a conservative score:

$$S_{\mathrm{robust}} = \min\left(S, S_{\mathrm{min,LOO}}\right)\,. \tag{4}$$

Table 2: Symbol definitions for robustness metrics.

Symbol	Definition
$S_{\mathrm{min,LOO}}$	Minimum significance under leave-one-out removal (dimensionless)
S_{robust}	Conservative RV variability score (dimensionless)
$\Delta \mathrm{RV}_{\max}^{(j)}$	Maximum RV difference with epoch j removed ($\mathrm{km\,s^{-1}}$)

We also track a leverage metric

$$d_{\max} = \max_i \frac{\left|\mathrm{RV}_i - \overline{\mathrm{RV}}\right|}{\sigma_{\mathrm{RV},i}}\,, \tag{5}$$

where $\overline{\mathrm{RV}}$ is the weighted mean RV. We flag stars with $d_{\max} > 100$ as "high-leverage" cases where a single epoch dominates the variability signal.

We form an initial candidate list by requiring $N \geq 3$ and $S_{\rm robust} \geq 10$.

Table 3: Symbol definitions for the leverage metric.

Symbol	Definition
$d_{\max}$	Maximum standardized residual (dimensionless)
RV_i	RV at epoch i ($\mathrm{km\,s^{-1}}$)
$\overline{\mathrm{RV}}$	Weighted mean RV over all epochs ($\mathrm{km\,s^{-1}}$)

4 Multi-Messenger "Negative Space" Validation

From the RV-variability shortlist we apply a secondary validation pipeline designed to identify systems with strong gravitational signatures but little or no additional light from the companion. A star is promoted to the unseen-companion candidate list if it satisfies:

1. **Gaia astrometry:** Elevated Renormalized Unit Weight Error (RUWE > 1.4) and/or significant astrometric excess noise, indicating that a single-star astrometric model is a poor fit. This is consistent with binarity but does not directly constrain companion mass.
2. **WISE/2MASS SED:** WISE color $W1 - W2 < 0.1$ and a Gaia+2MASS+WISE spectral energy distribution consistent with a single late-type dwarf, disfavoring luminous cool main-sequence companions that would produce infrared excess.
3. **TESS photometry:** No deep eclipses and no strong coherent modulation at the 10^{-4} level, disfavoring short-period contact binaries and highly tidally distorted systems with large mass ratios.
4. **GALEX UV imaging:** Non-detection in GALEX NUV, ruling out a hot ($T_{\rm eff} \gtrsim$ 10,000 K) white dwarf companion. Cool, old white dwarfs remain fully allowed.
5. **Legacy Survey imaging:** DECaLS imaging consistent with a clean, isolated point source, reducing the likelihood that high RUWE is driven by blending or crowding.

These criteria eliminate many obvious luminous companions and imaging pathologies; they do not uniquely identify compact objects, particularly since cool white dwarfs are neither UV-bright nor IR-luminous.

5 Top Candidate: Gaia DR3 3802130935635096832

5.1 Per-Epoch RVs and LAMOST Cross-Match

For the most interesting system, Gaia DR3 3802130935635096832, we have four DESI RV epochs and one earlier LAMOST measurement:

Table 4: Per-epoch RV measurements for Gaia DR3 3802130935635096832.

Source	MJD	RV ($\mathrm{km\,s^{-1}}$)	σ_{RV} ($\mathrm{km\,s^{-1}}$)
LAMOST	57457.000	-49.36	2.79
DESI	59568.48825	-86.39	0.55
DESI	59605.38003	$+59.68$	0.83
DESI	59607.37393	$+26.43$	1.06
DESI	59607.38852	$+25.16$	1.11

The DESI measurements alone span $\Delta\mathrm{RV}_{\mathrm{max}} = 146.07\ \mathrm{km\,s^{-1}}$ over a 38.9 day baseline. Two DESI epochs separated by 21 minutes agree at $< 1\sigma$, disfavoring very short-period (hours) solutions. The LAMOST RV, obtained 5.9 years earlier, lies between the DESI extrema and is consistent with orbital motion rather than a one-off outlier.

Using the DESI epochs with the definitions above we find:

- $S = 79.8$,
- $S_{\mathrm{min,LOO}} = 19.8$,
- $S_{\mathrm{robust}} = 19.8$,
- $d_{\mathrm{max}} \approx 113$ (the earliest DESI epoch is high leverage).

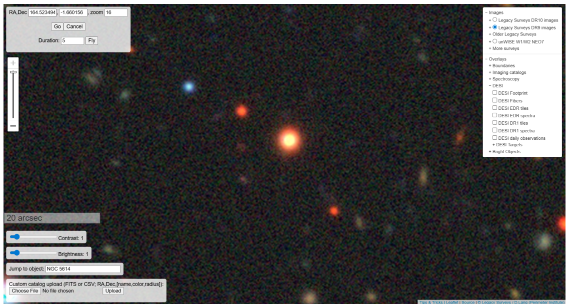
Thus the system is a secure RV variable even under leave-one-out removal, but its significance is partially dominated by one extreme epoch.

LAMOST classifies the visible star as an M0 dwarf (dM0). We adopt a primary mass $M_1 \approx 0.5\,M_\odot$ with a conservative bracket $M_1 \in [0.45, 0.6]\,M_\odot$.

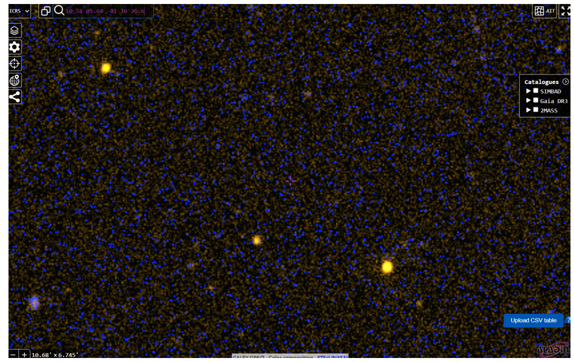
5.2 Astrometric, Infrared, and UV Properties

Gaia DR3 reports RUWE = 1.95 and significant astrometric excess noise, consistent with unresolved binary motion. WISE and 2MASS photometry yield $W1 - W2 = 0.052$ and an SED consistent with a single M0 dwarf, with no evidence for a luminous cool companion. GALEX NUV imaging shows no detection at the target position, disfavoring hot white dwarfs but leaving cool white dwarfs and compact objects entirely plausible.

Figure 1 illustrates the source isolation and UV non-detection.



(a) Legacy Survey (DECaLS) deep imaging. The source is a clean, isolated point source.



(b) GALEX NUV cutout. The target position (marked) is undetected, ruling out a hot, young white dwarf.

Figure 1: Imaging validation for Gaia DR3 3802130935635096832.

5.3 TESS Photometry

We extract TESS FFI photometry for the target and compute a Lomb–Scargle periodogram. The light curve shows no eclipses and no significant periodic signal. We place an approximate 95% upper limit on coherent modulation of $\sim 4.6 \times 10^{-4}$ in relative flux over periods from ~ 0.2 to ~ 10 days. This disfavors short-period contact binaries and highly distorted systems, but does not strongly constrain detached binaries at periods of tens of days, where expected ellipsoidal amplitudes are well below our detection threshold.

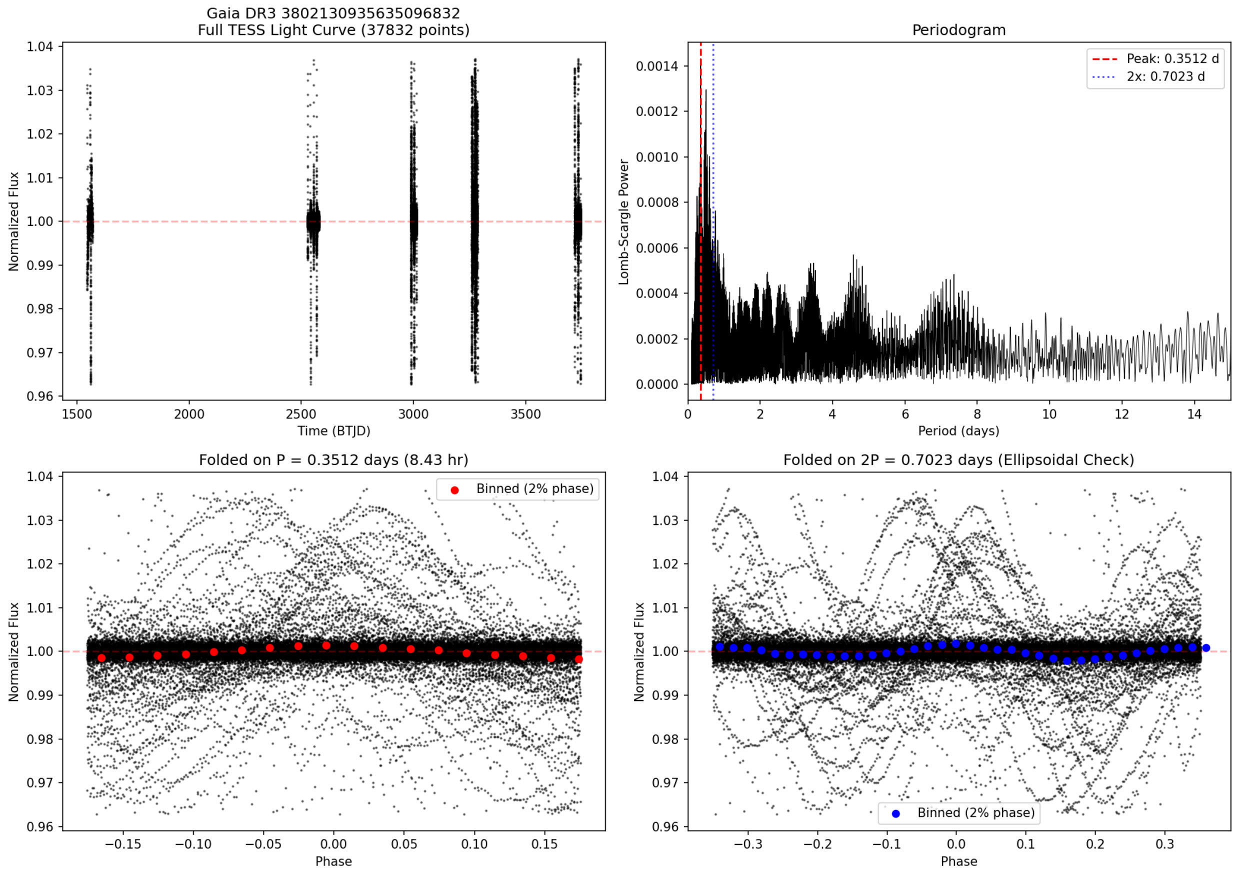


Figure 2: TESS analysis for Gaia DR3 3802130935635096832. Left: detrended TESS light curve showing no large-amplitude variability. Right: Lomb–Scargle periodogram; peaks are below the adopted significance threshold.

We summarize the "gravity versus silence" view in Figure 3, which juxtaposes the DESI RV time series with the essentially flat TESS light curve.

money_plot.png

Figure 3: "Money plot" for the candidate system. Left: DESI RVs show large velocity excursions. Right: TESS photometry is nearly flat, with no eclipses or strong modulation, indicating that the companion contributes little or no light.

6 Circular-Orbit Period Search (Illustrative)

6.1 Model and Definitions

To explore which orbital periods are consistent with the five available RV epochs we fit a simple circular-orbit model:

$$\mathrm{RV}(t) = \gamma + K \sin\left(\frac{2\pi t}{P} + \phi_0\right) , \tag{6}$$

where we solve for the period P, semi-amplitude K, systemic velocity γ, and phase offset ϕ_0 by minimizing χ^2.

Table 5: Symbol definitions for the circular-orbit RV model.

Symbol	Definition
$\mathrm{RV}(t)$	Model radial velocity as a function of time ($\mathrm{km\,s^{-1}}$)
t	Time of observation (MJD)
P	Orbital period (days)
K	RV semi-amplitude of the primary star ($\mathrm{km\,s^{-1}}$)
γ	Systemic (center-of-mass) velocity ($\mathrm{km\,s^{-1}}$)
ϕ_0	Phase offset at $t = 0$ (radians)
χ^2	Sum of squared residuals weighted by uncertainties (dimensionless)

We perform a grid search over $P \in [5, 100]$ days. At each trial period we optimize K, γ, and ϕ_0 using non-linear minimization and record the best-fit χ^2. This procedure identifies families of circular solutions that interpolate the sparse RV time series; it does not provide a unique or high-precision period measurement.

6.2 Illustrative Best-Fit Solution

One particularly good circular solution has

- $P_{\mathrm{fit}} \approx 15.9$ days,
- $K_{\mathrm{fit}} \approx 104\ \mathrm{km\,s^{-1}}$,
- $\gamma_{\mathrm{fit}} \approx -44\ \mathrm{km\,s^{-1}}$,
- reduced $\chi^2 \approx 0.32$ (with one nominal degree of freedom).

This fit reproduces all five RV epochs within their quoted uncertainties and passes internal consistency checks (e.g. same-night stability, TESS non-detection of ellipsoidal variations at the predicted amplitude).

Assuming $e = 0$ and following the standard spectroscopic mass-function relation, the mass function for this solution is

$$f(M) = \frac{PK^3}{2\pi G} = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2}\,, \tag{7}$$

where G is the gravitational constant, M_1 and M_2 are the primary and companion masses, and i is the inclination.

Table 6: Symbol definitions for the mass function.

Symbol	Definition
$f(M)$	Spectroscopic mass function (in solar masses, $M_\odot$)
P	Orbital period (days)
K	RV semi-amplitude ($\mathrm{km\,s^{-1}}$)
G	Gravitational constant ($\mathrm{m^3\,kg^{-1}\,s^{-2}}$)
M_1	Mass of the visible primary star ($M_\odot$)
M_2	Mass of the unseen companion ($M_\odot$)
i	Inclination angle (radians or degrees; enters via $\sin i$)

For $P = 15.9$ days and $K = 104\ \mathrm{km\,s^{-1}}$ we obtain $f(M) \approx 1.85\,M_\odot$. Adopting $M_1 = 0.5\,M_\odot$ and $\sin i = 1$ (edge-on), the minimum companion mass is $M_{2,\mathrm{min}} \approx 2.6\,M_\odot$, formally in the neutron-star / low-mass black-hole regime.

Figure 4 summarizes the period search and mass constraints for this illustrative circular solution.

period_search_results.png

Figure 4: Circular-orbit period search and illustrative mass constraints for Gaia DR3 3802130935635096832. Top left: χ^2 as a function of trial period, with the best-fit period at $P \approx 15.9$ days indicated. Top right: RV time series with the best-fit circular model overplotted (LAMOST epoch in blue, DESI epochs in red). Bottom left: phase-folded RV curve for the same solution. Bottom right: minimum companion mass $M_{2,\min}$ versus period for several assumed primary masses; shaded bands indicate approximate white-dwarf, neutron-star, and black-hole regimes. The red star marks the illustrative circular solution at $P \approx 15.9$ days and $M_{2,\min} \approx 2.6\, M_\odot$.

6.3 Caveats on the Period and Mass

Despite the excellent fit, several caveats prevent us from promoting $P_{\rm fit}$ to a measured orbital period:

- Only five RV epochs are available, with four clustered within 39 days and one point 5.9 years earlier; multiple discrete periods yield comparably low χ^2 when K, γ, and ϕ_0 are allowed to float.
- The assumption of a circular orbit ($e = 0$) is untested; allowing eccentricity would introduce additional families of solutions.
- Formal uncertainties on P, K, and M_2 are strongly non-Gaussian and multi-modal; the single best-fit value is illustrative rather than definitive.

To capture this more robustly, we also explore a conservative lower bound using only the DESI $\Delta\mathrm{RV}_{\rm max}$: $K_{\rm min} \approx \Delta\mathrm{RV}_{\rm max}/2 \approx 73\ \mathrm{km\,s^{-1}}$. For periods in the range $P \sim$ 20–40 days and $M_1 \approx 0.5\,M_\odot$, this conservative K still implies minimum companion masses of order 1.5–2.5 $M_\odot$; only for shorter periods or lower true K values does the minimum mass fall comfortably into the ordinary white-dwarf regime. Short periods ($\lesssim 1$ day) are strongly disfavored by same-night RV stability and TESS ellipsoidal limits. Thus, while a cool white dwarf cannot yet be excluded, the data are naturally pushing the companion mass into the heavy white-dwarf / neutron-star / black-hole region.

7 Discussion

The DESI DR1 per-epoch RVs, combined with Gaia, WISE, TESS, GALEX, Legacy Surveys, and LAMOST, allow us to identify and characterize a small number of high-amplitude RV-variable systems consistent with unseen companions. For Gaia DR3 3802130935635096832, several lines of evidence point toward an unseen compact companion:

- large DESI RV excursions and a LAMOST RV consistent with orbital motion,
- elevated Gaia RUWE and astrometric excess noise,
- infrared colours consistent with a single M0 dwarf and no luminous cool companion,
- non-detection in GALEX NUV, ruling out hot white dwarfs,
- absence of large-amplitude TESS variability, disfavoring contact binaries and very short periods.

When these are combined with the M0 primary classification ($M_1 \approx 0.5\,M_\odot$) and reasonable assumptions about the orbital period, the minimum companion mass is naturally driven into the heavy white-dwarf / neutron-star / black-hole regime. The illustrative circular solution at $P \approx$ 15.9 days and $M_{2,\rm min} \approx 2.6\,M_\odot$ makes the system a particularly interesting compact-companion candidate, but the sparse RV sampling precludes a definitive classification.

The key scientific value of the present work is therefore twofold: (i) a demonstration that DESI DR1 can be used for reproducible, survey-scale RV-variability searches for unseen companions, and (ii) the identification of Gaia DR3 3802130935635096832 as a strong compact-companion *candidate* that merits dedicated spectroscopic monitoring.

8 Limitations

Several important limitations of the current analysis should be emphasized:

1. **No uniquely measured period:** The five available RV epochs admit multiple circular-orbit solutions with comparable χ^2. The period $P \approx 15.9$ days should be treated as illustrative, not as a uniquely measured value.

2. **Sparse RV sampling:** Four DESI epochs are clustered within 39 days, and one LAMOST epoch precedes them by 5.9 years. This configuration is insufficient to tightly constrain period or eccentricity.

3. **High-leverage epoch:** One DESI epoch contributes disproportionately to the variability significance; although $S_{\rm robust} \approx 19.8$ remains large, this leverage structure motivates caution.

4. **Companion-type ambiguity:** While the "negative space" diagnostics disfavor luminous main-sequence companions and hot white dwarfs, cool white dwarfs, neutron stars, and black holes all remain viable, depending on the true orbital period and inclination.

5. **Astrometric interpretation:** Elevated RUWE and astrometric excess noise indicate non-single-star behaviour but do not by themselves measure companion mass.

9 Conclusions and Future Work

We have performed a conservative, reproducible RV-variability search using DESI DR1 MWS per-epoch RVs, combined with a multi-messenger "Negative Space" validation pipeline. Among the resulting candidates, Gaia DR3 3802130935635096832 stands out as a high-amplitude RV-variable system with an M0 dwarf primary, no obvious luminous companion, and strong indications of an unseen massive object.

At present, however, the system must be regarded as an *unseen-companion candidate*. The existing data are insufficient to determine a unique orbital period or a precise mass function, and the companion could be a massive white dwarf, a neutron star, or a black hole. The next decisive step is dedicated spectroscopic follow-up: a campaign with a cadence designed to (i) test for periods of order days through closely spaced observations and (ii) probe longer periods (tens of days) via observations spaced over months. Once the period P, semi-amplitude K, and eccentricity e are measured, the mass function can be determined and the nature of the unseen companion can be established.

Regardless of the final classification of this particular system, the methods developed here—including RV-variability metrics, robustness diagnostics, and the "Negative Space" pipeline—provide a general framework for compact-companion searches in DESI and other large spectroscopic surveys.

Data and Code Availability

All analysis scripts, configuration files, and derived products used in this work are publicly available at:

`https://github.com/simulationstation/DESI-BH-CANDIDATE-SEARCH`

and are designed to be fully reproducible with public DESI DR1 data.